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PLANT REMAINS AND RELATED SUBSTANCES IN THE PAST LACUSTRINE SEDIMENTS OF THE MT. RIISER-LARSEN AREA, ENDERBY LAND, EAST ANTARCTICA

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Abstract: Fragments of protonematoid moss plants remains, and empty shells seldom containing a plastid debris of epiphytic and free-living diatoms of *Achnanthes* and *Pinnularia* were found in the laminated muddy sediments formed in the past lacustrine environment of Lake Richardson in the vicinity of Mt. Riiser-Larsen, Enderby Land, East Antarctica. Chlorophyll derivatives, certain hydrocarbons and fatty acids were detected in the sediments. Among them long-chain *n*-alkanes ($\geq$C20) may have originated from the mosses while short-chain *n*-alkanoic acids ($\leq$C20) can be attributed to diatoms.

A large quantity of crystals of vivianite found in the sediments seems to have been produced in the phosphate-rich brackish water bodies under anoxic reducing conditions. That is, the bottom of an inlet of the past Lake Richardson would have penetrated far into the river mouth where the estuarine water could have been markedly affected by activities of some sea birds such as penguins.

1. Introduction

The Mt. Riiser-Larsen area is situated on the coast of Amundsen Bay, Enderby Land, East Antarctica. YOSHIDA and MORIWAKI (1983) conducted a preliminary study of the landform in this area and pointed out the existence of fluvioglacial deposits. A field party of the 29th Japanese Antarctic Research Expedition (JARE-29) visited the area in February 1988 and carried out biological, geomorphological and geological surveys. The past lacustrine sediments have been discovered in the fluvioglacial valley by a geomorphologist in the party. The purpose of this paper is to note the characteristics of these sediments and to examine the plants remains and related substances.

2. Results and Discussion

2.1. *Landform of Mt. Riiser-Larsen area and sampling location*

The Mt. Riiser-Larsen area stretches about 15 km long east-west and 6 km wide

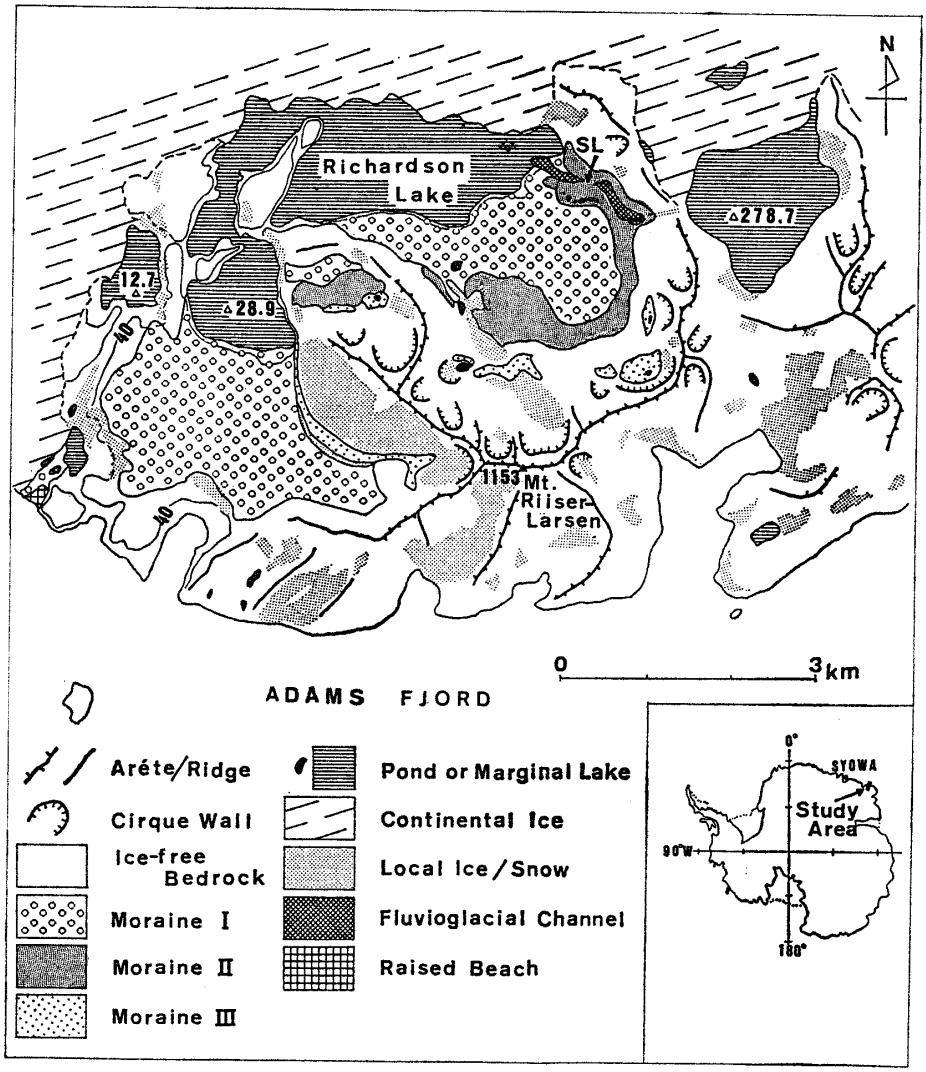

Fig. 1. Geomorphological map of the Mt. Riiser-Larsen area. SL; sampling locality of the past lacustrine sediments. Contour line of 40 m is drawn only in the western part. Arabic figures show elevations (m) above sea level.

north-south. The south end faces a deep inlet named Adams Fjord and the north is bounded by the ice sheet which extends from east to west. The mountain in maximum height of 1153 m above sea level has been dissected by glacial and periglacial erosion to form aretes or knife ridges in most part. The low-lying basins are carved with the main and subordinate ridges on the northwestern sides. The bottom of these basins is covered with moraines. A geomorphological map of this area is shown in Fig. 1. Judging from the observation of erratics and glacial striae, the ice sheet had once flowed across this area from east to west, and occupied the part lower than at least 600 m in altitude.

Moraine I constitutes wide low-lying basins with a rather flat surface. Many of cobbles and boulders in the deposits are angular and apparently more weathered than the other moraines. Moraine I must have been deposited by the above-mentioned ice sheet during its retreat from this area. Moraine II adjoining the southern margin of Moraine I shows an uneven surface.

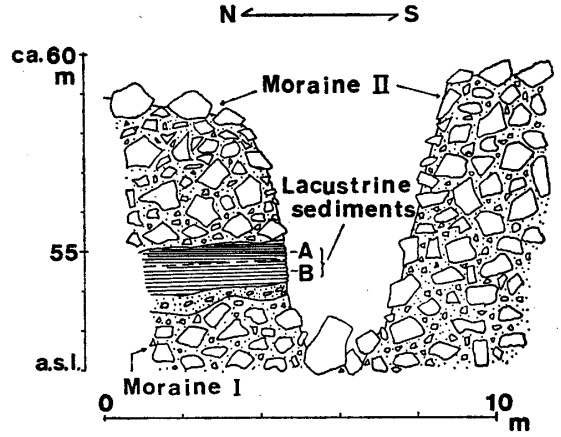

Fig. 2. Schematic cross profile of the fluvioglacial valley. Past lacustrine sediments are found on the northern wall of the fluvioglacial valley. On the opposite southern wall, sediments are probably covered with the screes from moraines. A: the upper layer of lacustrine sediments. B: the lower layer of the lacustrine sediments.

YOSHIDA and MORIWAKI (1983) suggested that Moraine II was formed by cirque glaciers which occupied the north-facing mountain slopes, after the formation of Moraine I. Moraine III consists of small-scale heaps accumulated on cirque bottoms and protalus ramparts sometimes cover the surface of the moraine. This moraine was probably formed by shrunken cirque glaciers. A remarkable fluvioglacial valley is found to the east of Lake Richardson (Plate 1A). A meltwater channel extends about 2 km long from a small ice body of the valley head to Lake Richardson. A stream could not be seen during the survey period (February). The channel upstream cuts 3 to 4 m down the surface of Moraine II and spreads about 50 m wide. Boulders lie scattered on the floor. A small delta with a flat surface and composed of rather fine materials is located around the river mouth. Between the delta and the upstream valley floor, a conspicuous gorge is located, where the channel sharply cuts 5 to 10 m down the morainic deposits. The lacustrine sediments crop out about 10 m long and 1 m thick on the wall of this gorge (Fig. 2 and Plate 1B). Sediments are laminated mud with fine sand. These sediments can be divided into two layers by their color tone, though an unconformity was not clearly defined between the layers. The upper layer is light yellowish in color and 40 cm in thickness (A in Fig. 2). About 12 varves per 1 cm thick were calculated (Plate 1C). The lower layer is dark brownish in color and about 70 cm in thickness (B in Fig. 2). About 6 varves per 1 cm thick were observed.

It is suggested that these sediments were formed on the bottom of the past proglacial lake which expanded after the formation of Moraine I, because boulders of Moraine II overlie these sediments. Deltaic deposits of fluvioglacial channel are much younger than the lacustrine sediments because they were produced by fluvial erosion after the formations of Moraine II.

2.2. *Plants remains in the lacustrine sediments*

The plant remains found in the past lacustrine sediments of Lake Richardson are composed of two different ecological elements as a whole. Among them, bryophytan protonematoid plants which are usually known as terrestrial inhabitants were dominant (Plate 2A, B), though the gametophytan moss plants were not found. Aquatic habitat of some moss species has been reported from several brackish ponds in the vicinity of Syowa Station (AKIYAMA and OCHI, 1975; KANDA, 1982). These moss communities

(*Bryum* sp.) are developed mostly on the bottoms of shallow waters containing 700–4000 ppm of chloride ion, and they are composed mainly of conspicious protonematoid moss plants intermingled with a small amount of gametophytan moss plants. The protonematoid moss plant remains in the past lacustrine sediments are microscopic fragments of protonematoid filaments, often adhering to the surfaces of empty diatom shells. It is accordingly conceivable that these protonematoid moss communities were developed on the shallow bottom of the past Lake Richardson, and their fragments resulting from wave action would have been accumulated and deposited on the deeper anoxic bottom. It is also highly probable that the past lake water was brackish, judging from the recent aquatic habitats of protonematoid moss communities in the vicinity of Syowa Station.

The fragments of protonematoid moss remains have brownish cell walls. Most cells contain several or more discoid chloroplasts or their amorphous debris, most of which are green to yellowish green in color. Some chloroplasts clearly showed the iodine reaction due to the remaining starch (Plate 2F).

The planktonic remains are mostly empty diatom shells of several species. According to a preliminary taxonomic observation, these diatom communities are composed of at least 2 species of *Achnanthes* and 2 species of *Pinnularia* (Plate 2C, D, E), and no difference in their diatom composition was observed between the upper and lower layers. Occasionally, the diatom shells contain green and slightly shrunk chloroplasts (Plate 2E). A similar phenomenon is known in the past marine sediments distributed around the shore of Lake Hunazoko in Skarvsnes, east coast of Lützow-Holm Bay, Antarctica (AKIYAMA, 1975).

2.3. *Chemical constituents of lacustrine sediments*

The organic constituents of various Antarctic lacustrine sediments have been clarified by MATSUMOTO and his coworkers (1977, 1979, 1981a, b, 1982, 1983, 1984, 1985, 1987). Such organic constituents of various sediments have become of major interest as useful biomarker parameters of sedimentary paleoenvironment (MATSUMOTO, 1988). The hydrocarbons and fatty acids found in the studied sediments are summarized in Tables 1 and 2, and some examples of capillary gas chromatogram (TIC) and mass chromatogram (*m/z* 71) of hydrocarbons are given in Fig. 3. The compositions of hydrocarbons and fatty acids of the upper layer are similar to those of the lower layer, suggesting that the changes in the sedimentary environment were small. Among the hydrocarbons detected, long-chain *n*-alkanes ($\geq$C20) may have originated from mosses (HUNECK, 1983), and the contribution of diatoms might be very small. Triterpanes (Fig. 3) including some unidentified compounds may have come also from mosses and/or bacteria (OURISSON *et al.*, 1979; HUNECK, 1983). The pristane/phytane (Pr/Ph) ratios are believed to reflect the redox potential of the sedimentary environments. That is, those ratios in anoxic reducing environments are low but high in more oxidizing environments (DIDYK *et al.*, 1978). In our case, phytane was more abundant than pristane in both layers, implying that the past lacustrine sedimentary environment was in an anoxic reducing condition (Table 1).

Among the fatty acids detected, it is probable that short-chain ($<$C20) *n*-alkanoic acids have originated from ditatoms, while the sources of long-chain ($\geq$C20) *n*-alkanoic

Table 1. Hydrocarbons detected in the past lacustrine sediments from the adjacent area of Mt. Riiser-Larsen, Antarctica (listed only the substances identified and examined quantitatively).

Compound*	Content (μg/g of dry sediment)		Compound*	Content (μg/g of dry sediment)	
	Upper layer	Lower layer		Upper layer	Lower layer
n 15	0.05	ND	n 30	0.08	0.19
n 16	0.14	0.05	n 31	0.12	0.34
n 17	0.16	0.05	n 32	0.03	0.03
n 18	0.11	0.08	n 33	0.05	0.05
n 19	1.44	0.60	n 34	0.02	0.02
n 20	1.59	0.68	n 35	0.02	0.02
n 21	4.69	4.65	n 27 : 1	0.08	0.08
n 22	1.53	1.01	n 28 : 1	0.07	0.05
n 23	3.29	3.02	n 29 : 1	0.61	0.32
n 24	0.57	0.57	Pristane	0.03	ND
n 25	1.97	2.53	Phytane	0.17	0.11
n 26	0.42	0.51	Phytene (a)	0.20	0.08
n 27	1.44	2.21	Phytene (b)	0.15	0.07
n 28	0.30	0.55	Phytadiene	0.14	0.08
n 29	0.57	1.24	Total	20.04	19.19

* Carbon chain length; n denotes normal and pairs of Arabic numerals, for example 27 : 1, denote carbon chain length : number of double bonds, respectively. ND denotes not detected.

Table 2. Fatty acids detected in the past lacustrine sediments from the adjacent area of Mt. Riiser-Larsen, Antarctica (listed only the substances identified and examined quantitatively).

Compound*	Content (μg/g of dry sediment)		Compound*	Content (μg/g of dry sediment)	
	Upper layer	Lower layer		Upper layer	Lower layer
n 10	0.4	0.2	n 28	9.3	11.9
n 11	0.4	0.1	n 29	0.4	1.9
n 12	1.9	1.1	n 30	1.0	4.4
n 13	0.8	0.5	n 31	ND	0.2
n 14	8.2	5.5	n 32	ND	0.3
n 15	3.4	3.0	i 12	0.3	0.2
n 16	31.8	20.0	i 13	0.6	0.3
n 17	2.0	1.6	a 13	0.8	0.4
n 18	12.1	8.3	i 14	4.7	2.7
n 19	6.5	4.0	i 15	3.2	1.9
n 20	53.6	27.1	a 15	5.0	5.1
n 21	12.1	9.2	i 16	1.8	1.9
n 22	57.8	33.6	i 17	0.8	0.5
n 23	5.9	6.8	a 17	2.1	1.8
n 24	19.4	21.0	i 18	1.9	1.7
n 25	2.8	3.8	n 16 : 1	8.5	4.9
n 26	15.3	18.4	n 18 : 1	3.7	4.3
n 27	1.8	2.6	Total	280.3	211.2

* Carbon chain length; n, i and a denote normal, *iso*- and *anteiso*-alkanoic acids, respectively, and pairs of Arabic numerals, for example 16 : 1, denote carbon chain length:number of double bonds, respectively. ND denotes not detected.

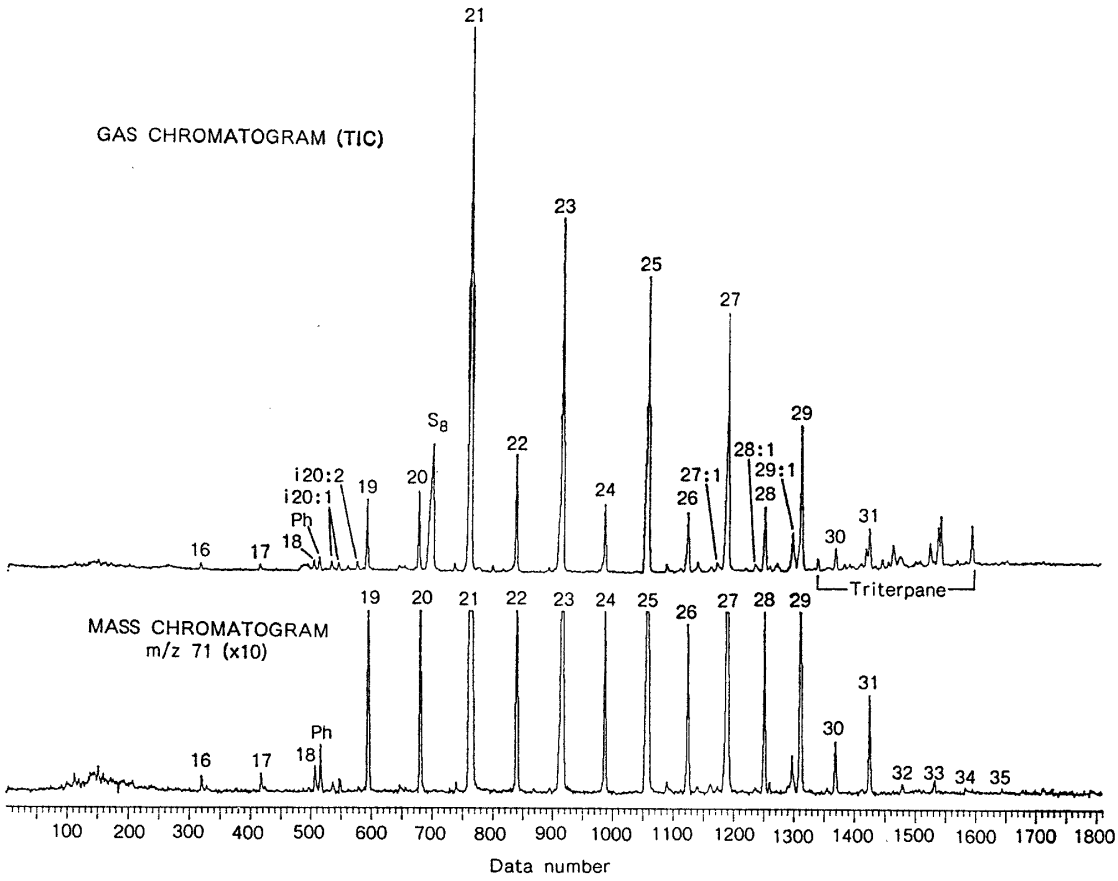

Fig. 3. Capillary gas chromatogram (TIC) and mass chromatogram (m/z 71) of the hydrocarbon fraction from the past lacustrine sediment (lower layer). Arabic numerals on the peaks denote carbon chain length of n-alkanes. Ph, i, and S8 denote phytane, isoprenoid, and sulfur, respectively. Pairs of Arabic numerals, for example 28 : 1 denote carbon chain length: number of double bonds, respectively.

acids are not clear, although mosses and microbial processes may be important, as suggested by the analytical results of fatty acids in soil samples and Beacon Supergroup sandstone samples with endolithic microbial communities from the McMurdo Dry Valleys (MATSUMOTO *et al.*, unpublished results). *Iso-* and *anteiso*-alkanoic acids are derived mainly from bacteria. Unsaturated fatty acids are considerably low and poly-unsaturated components were not be found. It seems that the unsaturated fatty acids were degraded *in situ* after the sedimentation. As noted previously, bryophytan proto-nematoid debris of plant remains and some diatom shells occasionally contain green-colored plastids. In this connection, the absorption spectra suggesting the presence of chlorophyll derivative (BOGORAD, 1962) were obtained from the methanolic extracts of the past lacustrine sediments (Fig. 4).

A large quantity of crystals of pyrite and vivianite was also detected from the sediments (Figs. 5, 6 and Table 3), by means of an electron prove microanalyzer. It seems that these substances were also produced in phosphate-rich brackish water in an anoxic reducing environment as already noted by LARSEN and CHILINGAR (1967). Accordingly, it may be suggested that the past sedimentary condition of our materials corresponds to such environment as the bottom of an inlet which penetrated far into the river mouth

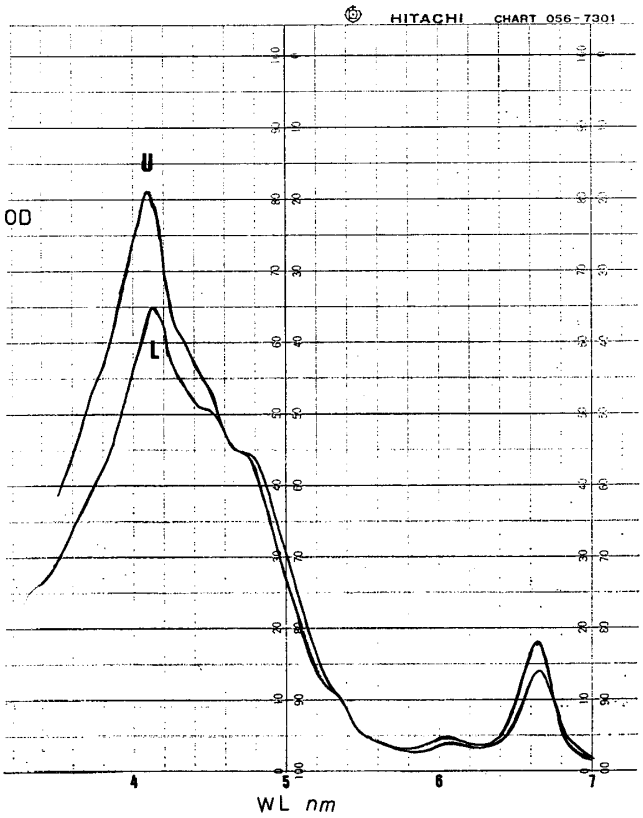

Fig. 4. Absorption spectra of the methanolic extracts of the past lacustrine sediments. U; upper layer, L; lower layer.

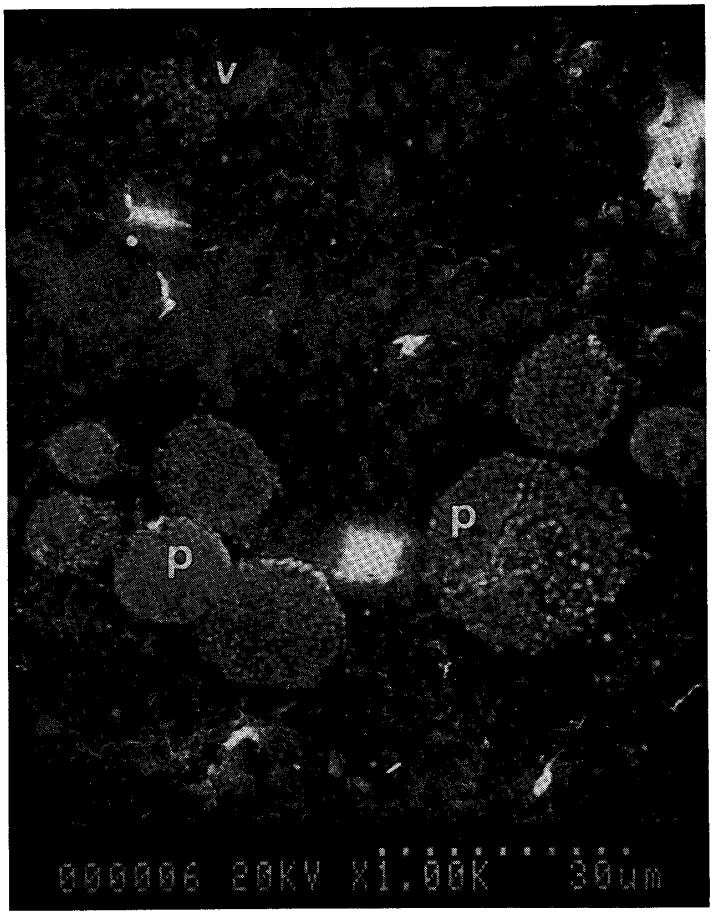

Fig. 5. Electron microscopic photograph of past lacustrine sediments. p; pyrite, v; vivianite.

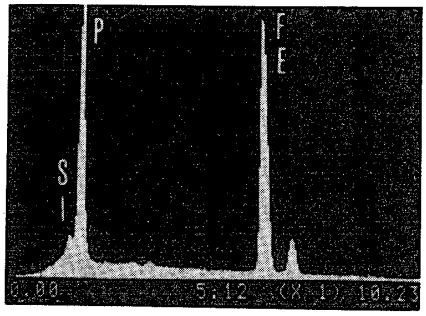

Fig. 6. X-ray spectrograph of vivianite. SI; silicon, P; phosphorus, FE; total iron.

Table 3. Chemical composition of vivianite found in the past lacustrine sediments at Mt. Riiser-Larsen, Antarctica.

Wt%		Atomic ratio		Wt%		Atomic ratio	
SiO_2	5.54	Si	1.45	Na_2O	0.60	Na	0.30
Al_2O_3	1.02	Al	0.32	K_2O	0.14	K	0.05
FeO	41.62	Fe	9.14	P_2O_5	29.76	P	6.62
MnO	0.26	Mn	0.57	S	0.23	S	0.11
CaO	0.54	Ca	0.15	H_2O	19.76	O	46.97
MgO	0.55	Mg	0.22	Total	100.00	H	34.62

where the estuarine water was provided with phosphate due to activities of some sea birds like penguins, while the water near the surface of the bottom was in an anoxic condition caused by the bacterial decomposition of accumulated autocthonous plants such as moss protonema and diatoms.

Of a special interest is the occurrence of vivianite which is not so common as pyrite in lacustrine sediments, though recently the presence of vivianite crystals in Antarctic soils was recognized by TATUR (1990). He found them from deep layers of ornithogenic soils developed in an abandoned penguin rookery area.

3. Experimental Procedure

The analytical methods of hydrocarbons and fatty acids were reported elsewhere (MATSUMOTO *et al.*, 1979). Describing briefly, sediments samples (*ca.* 6 g) were refluxed with 0.5 N potassium hydroxide in methanol (80°C, 2 h). The saponified samples were centrifuged ($\times 1000\,g$). The supernants and residues were acidified with concentrated hydrochloric acid and extracted with ethyl acetate. The ethyl acetate extracts were chromatographed on a silica gel column (160 × 5 mm i.d., 100 mesh, 5% water). Hydrocarbons and fatty acids were eluted with 2 column volumes of hexane and 3 column volumes of benzene/ethyl acetate (96/5), respectively. Fatty acid fractions were methylated with 14% borontrifluoride in methanol (80°C, 2 h). Hydrocarbons and fatty acid methyl esters were analyzed using a Shimadzu GCMS-QP1000 gas chromatograph (TIC)-mass spectrometer. The analytical conditions were as follows: Fused silica capillary column (DB-5, 30 m × 0.32 mm i.d.). Cooled on column injection. Flow rate of helium carrier gas was 4.3 ml/min. Column temperature was programmed from 70 to 120°C at 25°C/min, and then 120 to 310°C at 6°C/min. Temperature of injector, molecular

separetor and ion source were maintained at 335, 320 and 250°C, respectively. Mass spectra were taken at 70eV at a speed of 1.3 s/scan (m/z 50–600) with the gain of 2.8.

The chemical characteristics of minerals were determined by a Hitachi scanning electronprobe microanalyzer, Model S-650 with an energy-dispersive analytical system (Horiba Corporation EMAX-2200).

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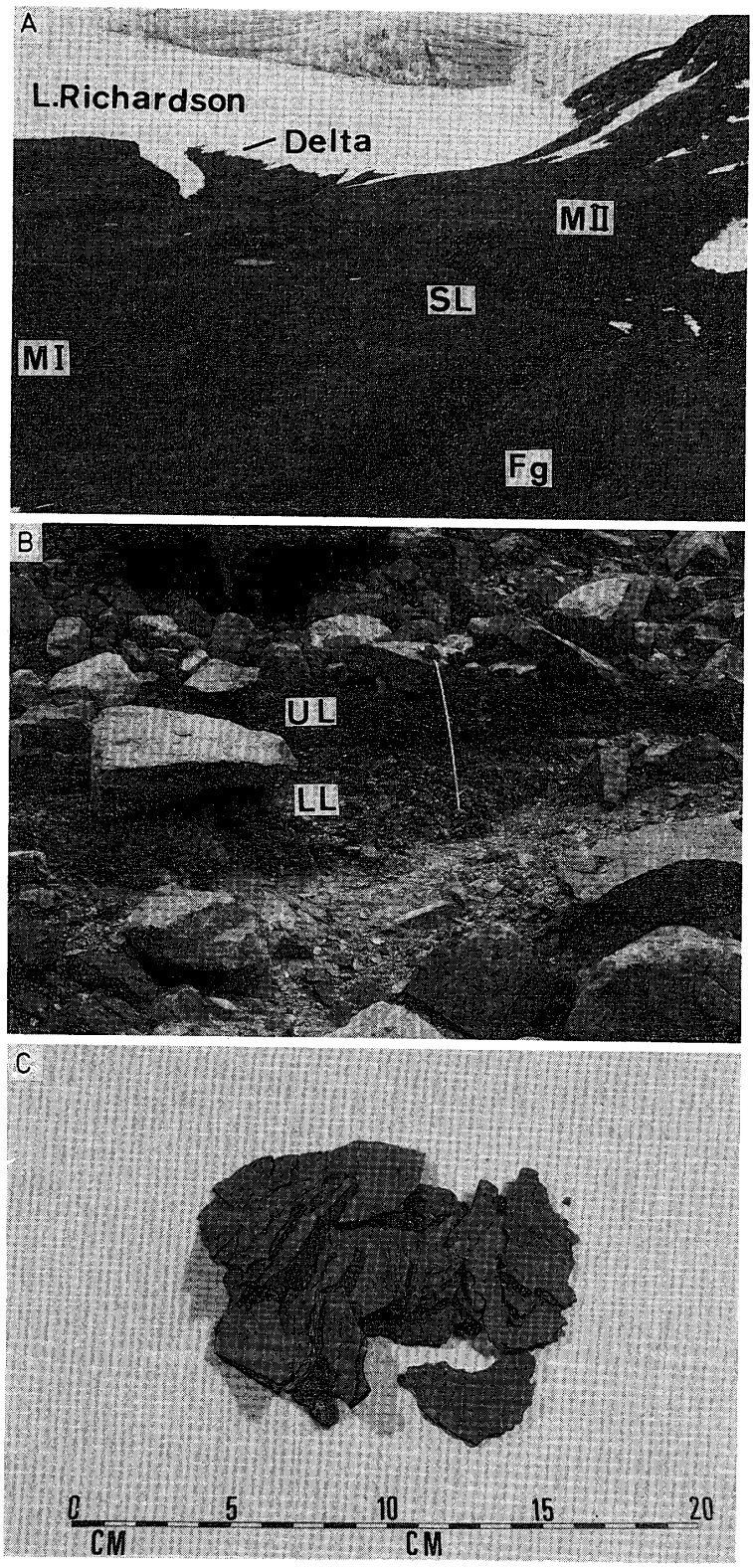

Plate 1. *A: A view of fluvioglacial channel and Lake Richardson. MI; Moraine I, MII; Moraine II, Fg; fluvioglacial channel, SL; sampling locality.*
B: Lacustrine sediments on the northern wall of fluvioglacial valley. The scale is about 1 m long. UL; the upper layer of lacustrine sediments. LL; the lower layer of lacustrine sediments.
C: Varved clay of the upper layer (A in Fig. 2).

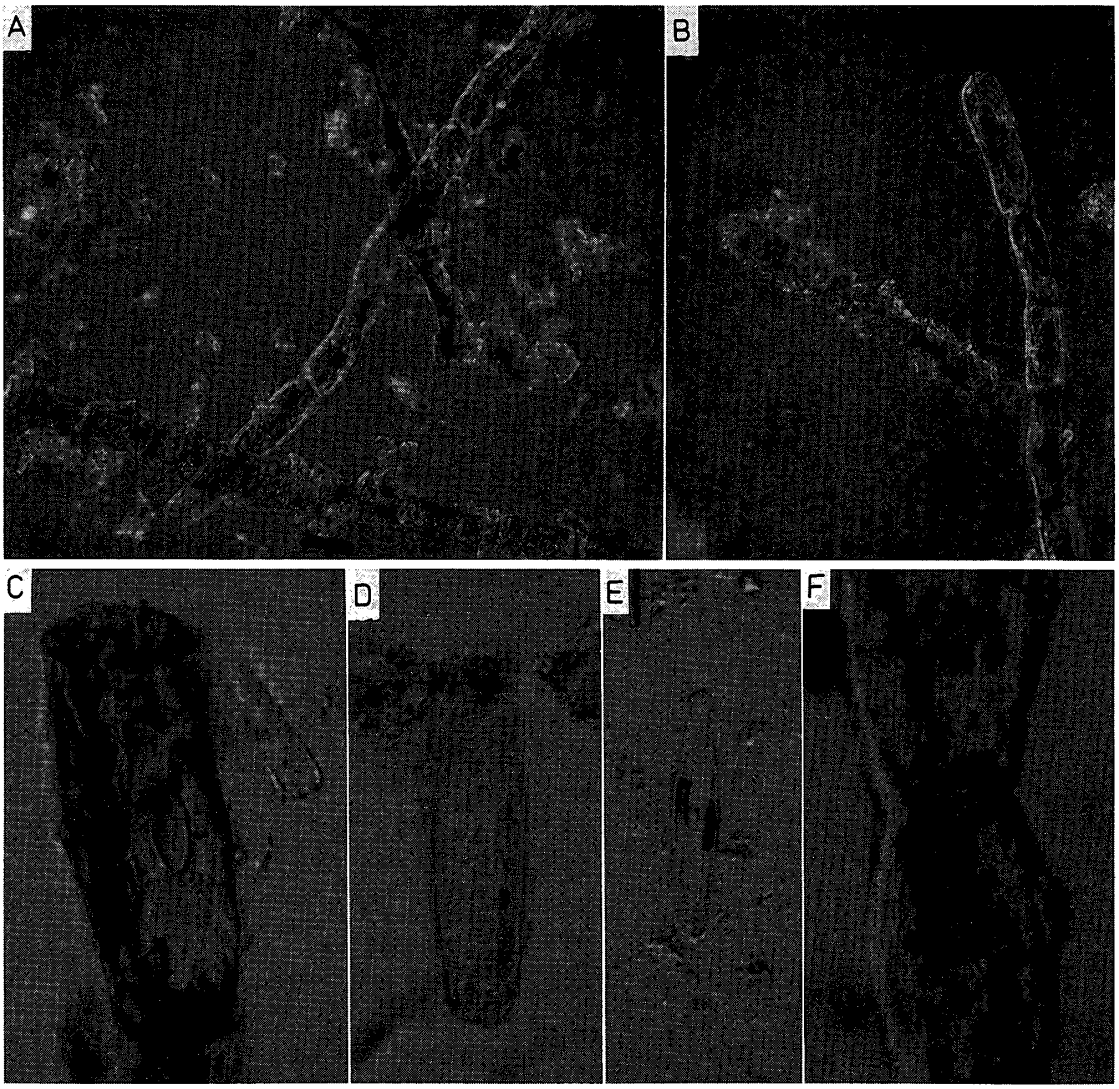

Plate 2. *A, B: Bryophytan protonematoids* (×*ca. 200*).
C: Bryophytan protonematoid cell with epiphytic diatom shells (×*ca. 600*).
D: Empty shell of Pinnularia *sp.* (×*ca. 600*).
E: Shell of Pinnularia *sp. containing chloroplast remains* (×*ca. 600*).
F: Bryophytan protonematoid cells containing discoid chloroplasts showing iodine reaction (×*ca. 600*).